REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-02-

0220

1. REPORT DATE *(DD-MM-YYYY)*
01/04/2002

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
15/03/1999 — 30/09/2002

4. TITLE AND SUBTITLE
New Integrated Components for Broadband Communication Systems

5a. CONTRACT NUMBER
F49620-96-1-0111

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Anand Gopinath, Richard Osgood

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Dept of Elec & Comp. Engineering
University of Minnesota
200 Union Street SE
Minneapolis, MN 55455

Department of Electrical Engineering
Columbia University
500 West 120 Street
New York, NY 10027

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. G. Pomrenke
Air Force Office of Scientific/NE
Randall Street
Arlington, VA

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE,
DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The objectives of this project was to design and fabricate polarization insensitive semiconductor optical amplifiers, design and fabricate planar optical isolators, investigate the possibility of their integration. Quantum well polarization insensitive semiconductor optical amplifiers in GaInAsP and AlInGaAs at 1300 nm, and the latter at 1550 nm were designed and tested, at Minnesota. Planar isolators in the Mach-Zehnder configuration were designed and tested at Columbia. The integration issues were investigated and a key component, the planar polarizer, was designed. Sputtered films for integration of the isolator were also investigated. For broadband system components, Minnesota examined the co-directional coupler, and arrived at a synthesis technique which does both amplitude and phase response. Columbia has examined the simulation of optical components and made considerable progress in practical simulation of mixed polarization devices. The report briefly outlines the results.

15. SUBJECT TERMS
semiconductor optical amplifiers, planar optical isolators, co-directional coupler, simulations

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		1+7	Anand Gopinath
					19b. TELEPHONE NUMBER *(include area code)* 612-625-3054

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

20020719 119

05-13-02P01:40 RCVD

New Integrated Optical Components for Broadband Communication Systems

Anand Gopinath and Richard Osgood
University of Minnesota and Columbia University

Introduction

The objectives of this MURI were to develop broadband integrated components for 1300 nm and 1550 nm fiber optic systems. The major task at the University of Minnesota, was to design and fabricate semiconductor optical amplifiers which are polarization insensitive at both 1300 nm and 1550 nm. The major task for Columbia University was to design, fabricate, and test a planar waveguide isolator. The joint tasks were to integrate these components, and, in addition to this major goal, the task of examining other components for wide band systems rested with both Universities, and the development of new simulation methods for integrated optical components also was also jointly shared.

The program has achieved its goals: Minnesota has designed and fabricated polarization insensitive semiconductor optical amplifiers, Columbia has designed and built Mach-Zehnder isolators. The integration of both of these devices has been investigated and the design of important secondary components such as integrated polarizers accomplished. Sputtered magnetic films for integration were also investigated. For broadband system components, Minnesota examined the co-directional coupler, and arrived at a synthesis technique which does both amplitude and phase response. Columbia has examined the simulation of optical components and made considerable progress in practical simulation of mixed polarization devices. In the following sections, the results of this program are briefly outlined.

Polarization Insensitive Semiconductor Optical Amplifiers

The semiconductor optical amplifiers are to be polarization insensitive so that elliptically polarized light may be amplified without loss due to polarization effects. The polarization insensitive structures may be implemented by a variety of techniques, and the simplest method is to place small tensile strain in the wells, so that the light hole band, which is depressed by the quantization of the well, is brought up to the heavy hole band, and this method was adopted for this project. The alternative widely used method of alternating tensile and compressive strained wells requires several growth iterations. To determine the required strain for the tensile strain approach, **k.p** program was written for both the InGaAsP and the AlInGaAs material systems. The polarization match the tensile strain value for the 1300 nm wavelength in InGaAsP material system was readily found. For the AlInGaAs system, the differences between the TE and TM mode gains were quite wide, but a compromise was accepted both the 1300 nm and 1550 nm band structures. The wafers were grown in InGaAsP for the 1300 nmm band, and AlInGaAs for the 1550 nm band. The wafers were processed to produce both lasers and amplifiers. The amplified spontaneous emission of the amplifiers at current drive below transparency is a sign of the gain equalization. Below is a typical measured result for the AlInGaAs amplifiers in the 1300 nm band. Results for devices in other materials and wavelengths show similar behavior.

Synthesis of Response Functions of Filters and Coupler Modulators

The inverse scattering and the Fourier transform technique may be used to synthesize the response function of the coupler filters and modulators. While the grating assisted contra-

directional coupler design has been examined in the literature, the synthesis of the response of the co-directional coupler modulator has not been previously discussed. Here the response is synthesized by varying the coupling between the guides. The coupling function also needs to become negative in specific regions of the coupler, and this is achieved by introducing a 180-degree phase shift in one of the guides by including an extra length, and at 1300 nm, this is of the order of 0.18 nm. The coupling function of a linear response coupler has been synthesized, and the coupler was designed to have a variable coupling by changing the spacing between the guides. Consequently, the switching voltage is large, and but nevertheless the device was built to test the concept. Figure 2 shows the dc response of the modulator, and with its two tone tests, showing a spur free dynamic range of about 90 dB.

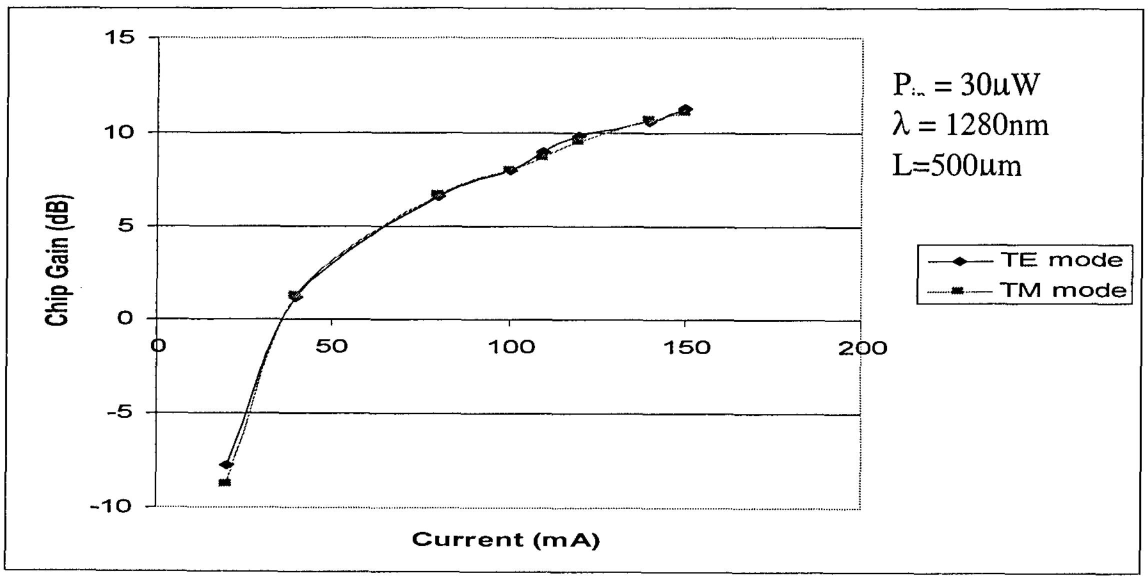

Figure 1. Measured gain for 0.33% tensile strained 100 nm quantum wells in AlInGaAs system for 1300 nm wavelength band.

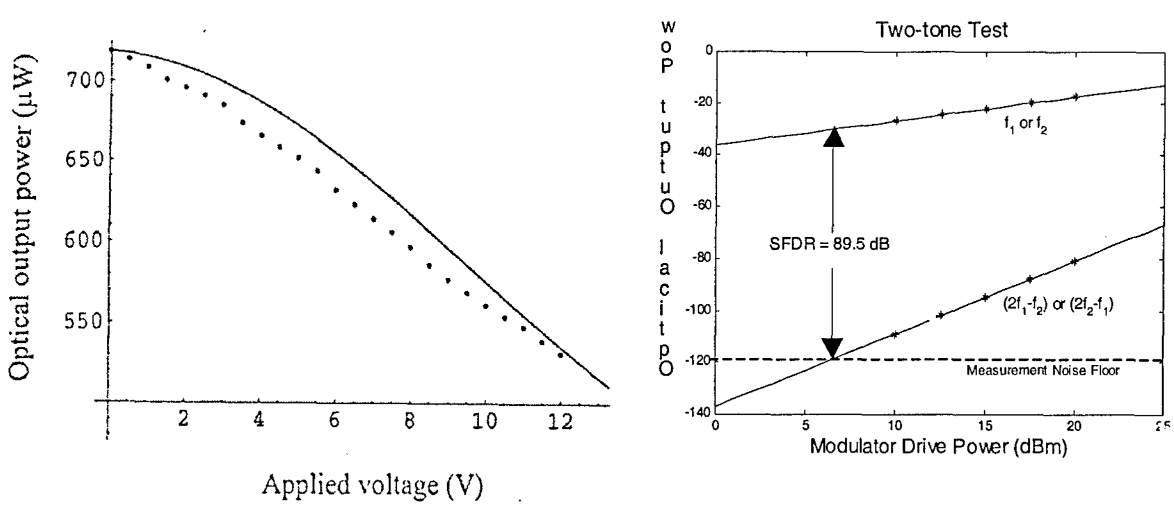

Figure 2: DC response of the linearized modulator, and the two-tone test results.

Reactive Sputtering for Integrated Isolators

The ultimate goal of this project was a waveguide isolator. Such a device would be advantageous because it could be integrated directly with a semiconductor optical amplifier or a laser. The three components necessary for an integrated isolator were explored, including the magneto-optical active layer, a biasing permanent magnet layer, and buffer/cladding layers. The most difficult, and yet most important layer is the magneto-optic active layer which was chosen to be yttrium iron garnet (YIG) due to its very high Faraday rotations .

Two techniques were attempted for YIG growth: dual-target and single-target reactive rf sputtering. In dual-target sputtering, 8" metallic Y and Fe targets were used to fabricate YIG films. The films were annealed up to 1200°C in air for 3 hours in order to study the effects of fluctuations in the Y:Fe ratio on the resulting crvstal structure. In single-target sputtering, Fe foil pieces were placed in a Fe:Y=3:1 ratio on a metallic Y target. Films were grown utilizing the sputtering unit mentioned above at rf powers of 15.4-18.5 W/cm^2. However, crystallized YIG films were grown *in situ*, without annealing, by increasing forward power & sputter pressure. Incorporation of Bi onto these patterned targets should increase the Faraday effect by a factor of 60. However, the thermal expansion coefficient also increases, and we are unable to grow films of the desired thickness.

MgO had the most potential for in situ crystallized YIG and we have previously found MgO to be effective in protecting semiconductor substrates during subsequent depositions. However, it appears that a compliant layer will be required to enable Bi-YIG to be grown on MgO due to the thermal expansion mismatch.

The properties of these *in situ* crystallized films were excellent for the purposes of this work. They were of high optical quality with indices measured to be 2.2. The magnetic properties were also very promising as shown below. They were ferromagnetic and isotropic. They could be saturated with SmCo permanent magnet films that are also grown by our group using sputtering, see below. Finally, the Faraday rotation through single-target sputtered films on MgO was measured with a 632.8 nm laser. The films possessed a ferromagnetic component of 0.175 deg/um. The incorporation of Bi into these films has a promised improvement factor of 60.

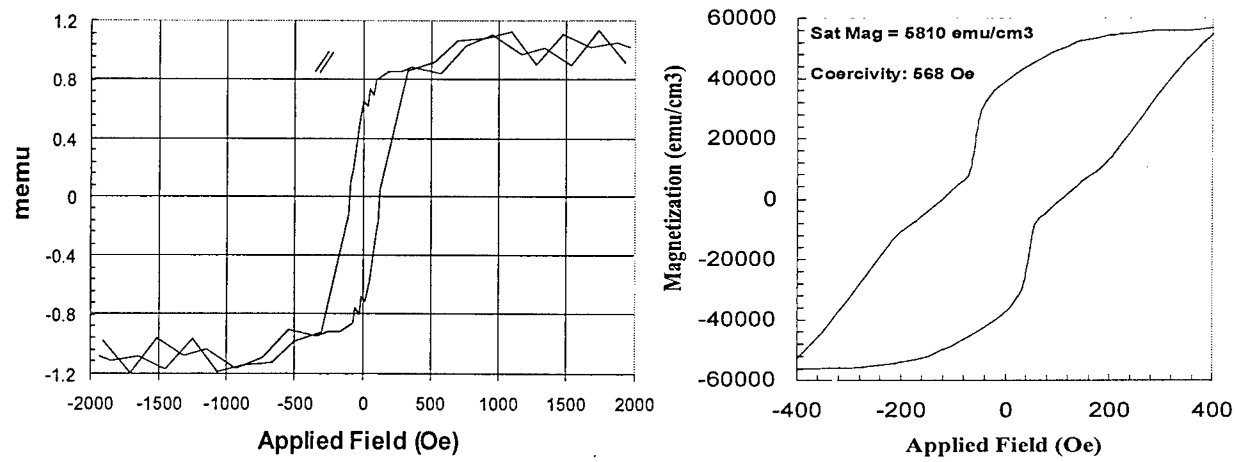

Figure 3: Magnetic hysteresis of YIG film crystallized on MgO *in situ* without substrate heat, and Magnetic hysteresis of SmCo permanent films.

Fabrication of Integrable Waveguide Isolators

Our work on integratable isolators has focused developing new forms of isolator designs that lend themselves to integration. This was an important goal since the standard isolator design that is currently used for bulk devices is based on the axial Faraday effect; this type of device requires the use of in-line polarizers, which are particularly complex to integrate using planar processing. In fact, our early work on isolators for this program did in fact develop new forms of polarizers and magnets that make hybrid integration of Faraday isolators possible. For example, this work yielded the first demonstration of a thin-film metal magnet for in useful micron-scale optical isolator and a new integratable semiconductor isolator.

Since then we have developed a novel Mach-Zehnder isolator which operates on very different principles than that of the axial Faraday rotator. In our device the non-reciprocal action is derived via the use of the transverse magneto-optical effect which is obtained via a transverse magnetic field applied across one or both arms of an integrated Mach-Zehnder interferometer. This non-reciprocal effect is also matched with a reciprocal effect in each arm of the interferometer. In the device the combination of the two effects cause light propagating through the device to interfere constructively in the forward direction and destructively in the backward direction. The initial phase of this work used a fiber-optic interferometer to measure the non-reciprocal phase shift and hence the off-diagonal magnetooptical tensor element for our YIG material. The Mach-Zehnder device was then fabricated in a thin sample of epitaxial YIG on GGG using ion-implantation and wet etching to pattern waveguides in the YIG. Optical transmission measurements were made on the device and the isolation ratio and the excess loss were measured. These are plotted in Fig. 4 below. The performance of this device, which is the first such device, is such that it is a practical approach to making an integrable optical isolator.

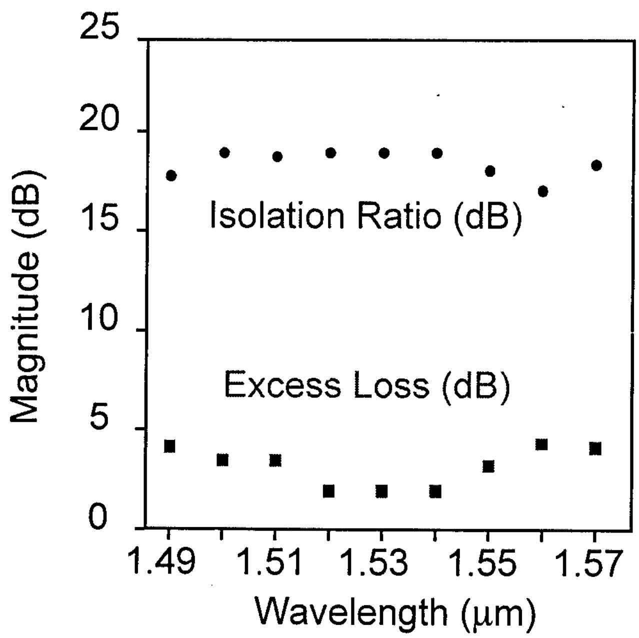

Fig. 4: A plot of the isolation ratio and excess loss for our Mach-Zehnder- based isolator

New Ultra-Thin-Film Single-Crystal YIG
One of the most important results from our program has been the development of a new method of fabricating micrometer thick films of high-quality YIG. Heretofore it has not been possible to obtain essentially bulk-quality films in such an ultra-thin form. The new process, which we have developed, is called crystal ion slicing (CIS) and uses ion damage in conjunction with selective wet etching to accomplish a lift-off of a film that is from 5-10micrometers in thickness. These films have been extensively characterized and are found to be of superior quality. They can be bonded to a semiconductor wafer via bonding. Isolator designs using these films are currently being pursued.

Integration Methods for YIG Devices on Semiconductors
Currently we are examining several new approaches to integrating the Mach-Zehnder isolator on the surface of a semiconductor wafer. The bonding approaches include wafer bonding and use of various adhesives. Development of wafer bonding required considerable work to develop a route to a practical surface chemistry, which would enable attainment of a useful bonding-processing window.

A second problem was to develop a procedure to bond the YIG device onto the wafer in such a way that the guided optical wave did leak into the substrate as a result of an unfavorable index match of the YIG and semiconductor materials structure. One approach to this problem is via the air gap structure shown in Fig. 5. This technique has recently been described in a paper accepted by PTL.

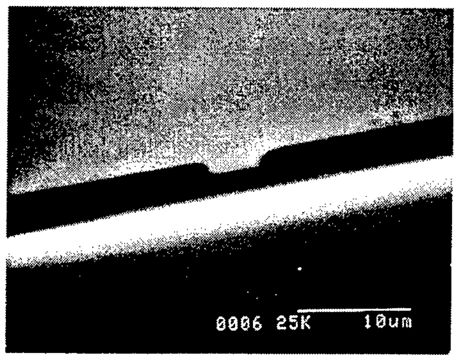

Fig. 5: YIG rib waveguide (top) bounded to InP wafer (bottom) with an air gap for optical isolation.

Photonic Crystals in Magnetooptical Materials
One of the last projects investigated on this program was to investigate the use of photonic crystal structures in magnetooptical materials. The advantage of such an approach is that it can provide a much shorter length isolator than is possible with standard magnetooptical designs. For example, we have used transfer matrix approaches to show that isolators as short as 50micrometers can be made using alternating thin slabs of dielectric and MO materials. Recently one of us has shown that a broadband version of this same device can also be designed.

Published papers:
Columbia
T. Izuhara, M. Levy, and Jr. Osgood, R.M. Direct wafer bonding and transfer of 10- micrometer-thick magnetic garnet films onto semiconductor surfaces. *Appl Phys Letts*, 76(10):1261-3, 2000.

Z. Huang, R. Scarmozzino, G. Nagy, J. Steel, and Jr. Osgood, R.M. Realization of a compact and single-mode optical passive polarization converter. *IEEE Photonics Techn Letts*, 12(3): 317-19, 2000.

J. Fujita, M. Levy, Jr. Osgood, R.M., L. Wilkens, and H. Dotsch. Waveguide optical isolator based on Mach-Zehnder interferometer. *Appl Phys Letts*, 76(16): 2158-60, 2000.

J. Fujita, M. Levy, Jr. Osgood, R.M., L. Wilkens, and H. Dotsch. Polarization-independent waveguide optical isolator based on nonreciprocal phase shift. *IEEE Photonics Techn Letts*, 12(11): 1510-12, 2000.

J. Fujita, M. Levy, R.U. Ahmad, Jr. Osgood, R.M., M. Randies, C. Gutierrez, and R. Villareal. Observation of optical isolation based on nonreciprocal phase shift in a Mach-Zehnder interferometer, *Appl Phys Letrs*, 75(7): 998-1000, 1999.

J. Fujita, M. Levy, and Jr Osgood, R.M. Nonperipheral cleaved facet fabrication technique, *IEEE Photonics Techn Letts*, 11(1): 78-80, 1999.

J. Fujita, M. Levy, R. Scarmozzino, Jr. Osgood, R.M., L. Eldada, and J.T. Yardley. Integrated multistack waveguide polarizer, *IEEE Photonics Techn Lets*, 10(1): 93-5, 1998.

M. Levy, Jr. Osgood, R.M., A. Kumar, and H. Bakhru. Crystal ion slicing of single-crystal magnetic garnet films, *J of Appl Phys*, 83(11): 6759-61, 1998.

M. Levy, Jr. Osgood, R.M., A. Kumar, and H. Bakhru. Epitaxial liftoff of thin oxide layers: yttrium iron garnets onto GaAs, *Appl Phys Letts*, 71(18):2617-19, 1997.

Published papers and Conference Presentations: Minnesota

Sangin Kim, Anand Gopinath, Vector analysis of dielectric waveguide bends, *J. Lightwave* Tech., Vol. 14, pp.2085-2092, 1996.

W. Yang, A. Gopinath, Design of planar optical waveguide corners with turning mirrors, *1996 Integrated Photonics Research Meeting Digest*, paper IMD1, pp.59-63, Boston, MA, April 29- May2, 1996, OSA.

Fuyun Lu, R. Freking, Anand Gopinath, High rate pulses from modelocked semiconductor laser diodes with DBR, *IEEE 1996 LEOS Annual Meeting Conference Proceedings*, Vol 2, pp.82-83, Boston, MA, November 1996.

Sigurd Lovseth, Chanin Laliew, A. Gopinath, Synthesis of the response of a coupler modulator using the Fourier Transform method, *1997 European Conference on Integrated Optics*, Stockholm, Sweden, April2-4, 1997.

Sigurd Lovseth, Chanin Laliew, Anand Gopinath, Synthesis of amplitude response of coupler modulators, *1997 IEEE International Microwave Symposium Digest*, pp.1717-1720, 1997.

Sangin Kim, A. Gopinath, Active Space division switch fabrics using semiconductor amplifiers, *Conference Proc. LEOS 97*, Vol 1, pp.202-203, Nov. 1997, San Francisco, CA, OSA.

Sangin Kim, A. Gopinath, Carrier induced partial screening of piezoelectric field in strained InGaAs based quantum wells grown on (111) substrate, *Conference Proc. LEOS 97*, Vol 2, pp.144-145, Nov. 1997, San Francisco, CA, OSA.

Sangin Kim, WoonJo Cho, Xiaobo Zhang, Mark Hopkinson, Anand Gopinath, Design of polarization insensitive semiconductor optical amplifiers at 1300 nm, *1998 Integrated Photonic Research Meeting Technical Digest*, pp.324-326, 1998, O.S.A.

P. R. Hayes, L. Miller, P. Woodward, M. O'Keefe, A. Gopinath, Numerical Modeling of Optical Waveguides, *International Workshop on Optical Theory and Numerical Modeling*, 18-19 September, 1998, Hagen, Germany (Invited paper).

C. Laliew, S. Lovseth, X. Zhang, A. Gopinath, Synthesis of response of coupler modulators, *IEEE Microwave-Photonics Topical Meeting*, 12-14 October, 1998, Princeton, NJ (Invited paper).

Chanin Laliew, Xiaobo Zhang, Ananad Gopinath, Linearized optical directional modulator, *Integrated Photonics Research Meeting*, July 1999, Santa Barbarra, CA.

William Berglund, Anand Gopinath, WKB analysis of optical waveguide bends, *Integrated Photonics Research Meeting*, July 1999, Santa Barbarra, CA.

P. R. Hayes, P. R. Woodward, M. O'Keefe, A. Gopinath, Higher order time domain scheme for solution of scattering problems, *IEEE 1999 International Microwave Symposium*, Annaheim, CA, June 1999.

P. R. Hayes, P. R. Woodward, M. O'Keefe, A. Gopinath, Time domain solutionsof optical waveguide problems with higher order schemes, *Quantum Electronics and Optics*, Vol. 31, no. 10, pp. 813 - 826, 1999.

R. Scaramozzino, A. Gopinath, R. Pregla, S. Helfert, Numerical techniques for modeling guided wave photonic devices, *IEEE J. Special Topics in Quantum Electronics*, Vol. 6, no 1, pp. 150-162, 2000. (Invited Paper).

C. Laliew, X. Zhang, A. Gopinath, Linear optical coupler modulator, *IEEE International Microwave Symposium*, Boston, MA, June 2000.

Prakash Koonath, Anand Gopinath: GaAs Polarization convertor, *Integrated Photonics Research Meeting Technical Digest*, pp. 171-173, Quebec City, Cananda, July 2000, OSA.

Prakash Koonath, Sangin Kim, Woon-Jo Cho, Anand Gopinath: Polarization insensitive semiconductor optical amplifiers in AlInGaAs , *Optical Fiber Communication Conference Technical Digest*, paper WDD-70 , Anaheim,CA, March 2001, OSA.

Prakash Koonath, Sangin Kim, Woon-Jo Cho, Anand Gopinath: Polarization insensitive semiconductor optical amplifiers in AlInGaAs, *IEEE Photonics Technology Letters*, vol.13, pp.779-81 2001.

T. Li, C. Laliew, A. Gopinath, An iterative transfer matrix inverse scattering technique for synthesis of co-directional optical couplers and filters *J. Quantum. Electronics*, Vol. 38, pp. 375 –379, 2002